Municipal Solid-State
STREET LIGHTING
CONSORTIUM

Sponsored by the U.S. Department of Energy

LM-79, LM-80, and other Challenges of the “Revolution”

May 19, 2011

Eric Haugaard
BetaLED by Ruud Lighting
Eric_Haugaard@ruudlighting.com

Mark McClear
Cree
Mark_McClear@cree.com

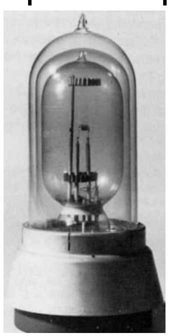
…A Brief History of Lighting

1879
Edison Light Bulb

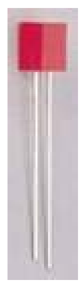
U.S. 223,898

1901
Fluorescent Tube

1919
Sodium Vapor Lamp



1970s
First Red LED



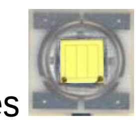
~1990
"High Brightness" Red, Orange, Yellow, & Green LEDs

1995
"High Brightness" Blue, Green LEDs

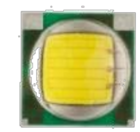
2000
White LED Lamp demonstrates Incandescent Efficacy (17 lm/W)

2005
White LED Lamp demonstrates Fluorescent Efficacy (70 lm/W)

2008
Production White LED Lamp Exceeds 100 lm/W

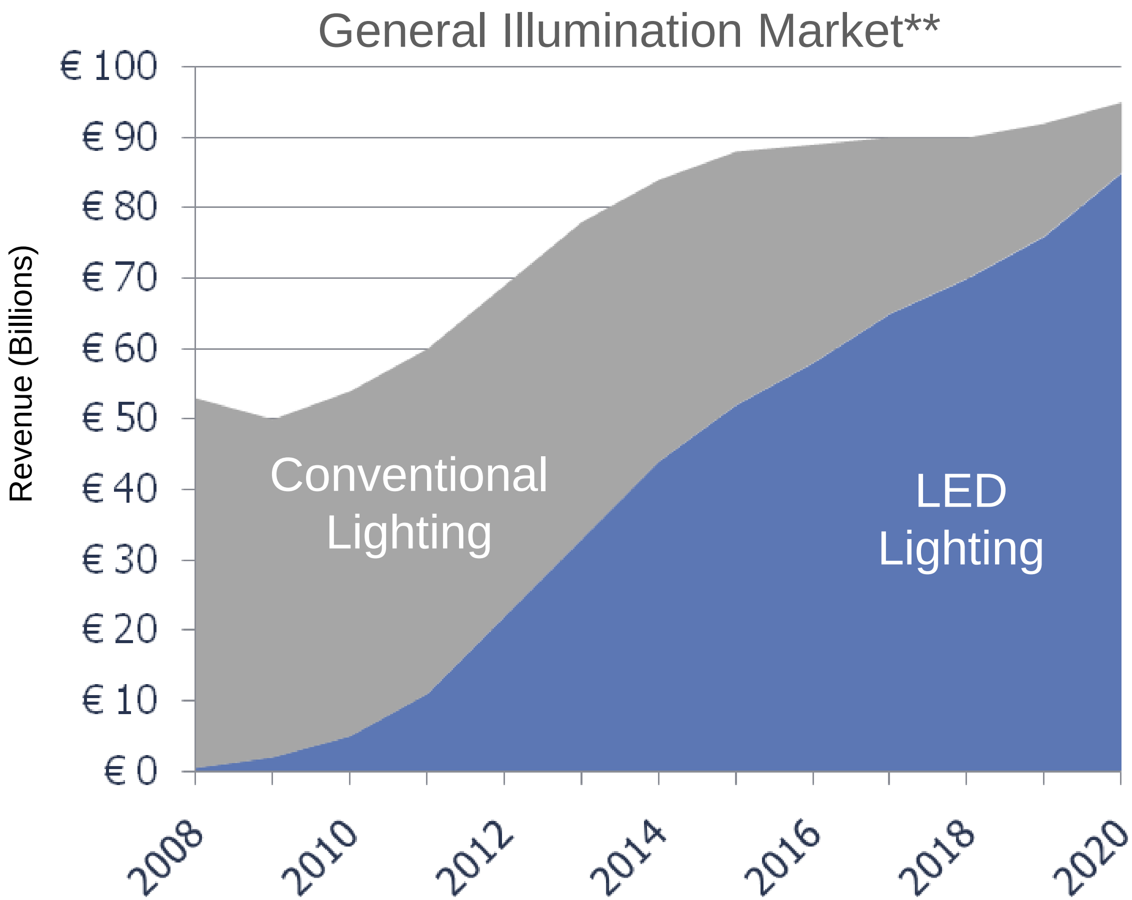


2010
White LED Exceeds 150 lm/W



LEDs began as just indicators, but have now become the most efficient light source ever created

Rapid Change is Coming to Lighting

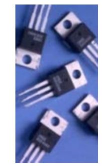


**Philips Lighting 2009

This Has Happened Before....

Vacuum Tubes → Transistors

1940s – 1960s



VHS → DVD

1980s – 1990s

CRT TV → Flat Panel TV and Displays

1990s – 2000s

Film → Flash Memory

1990s – 2000s

“Brick” phones → Smart phones

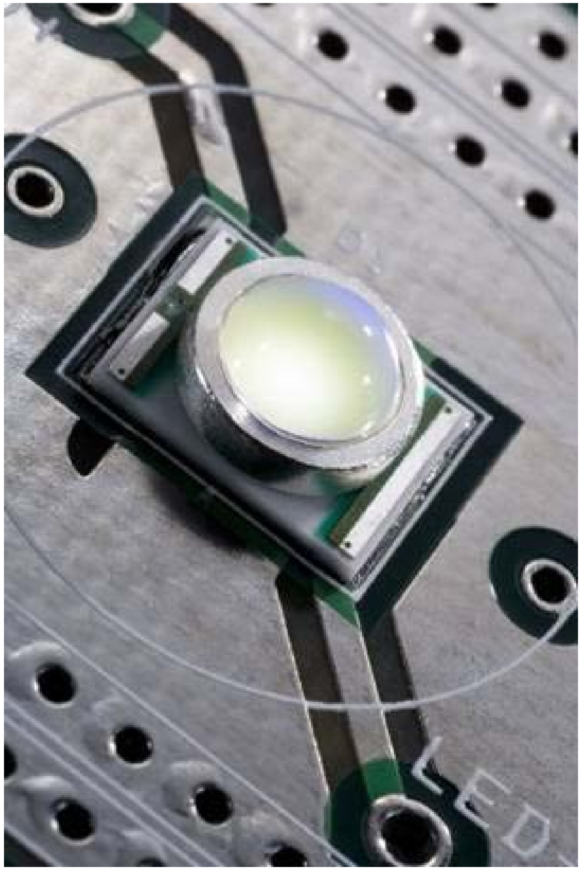
1990s – 2000s

Light Bulbs/ Fluorescent Tubes → Solid State Lighting

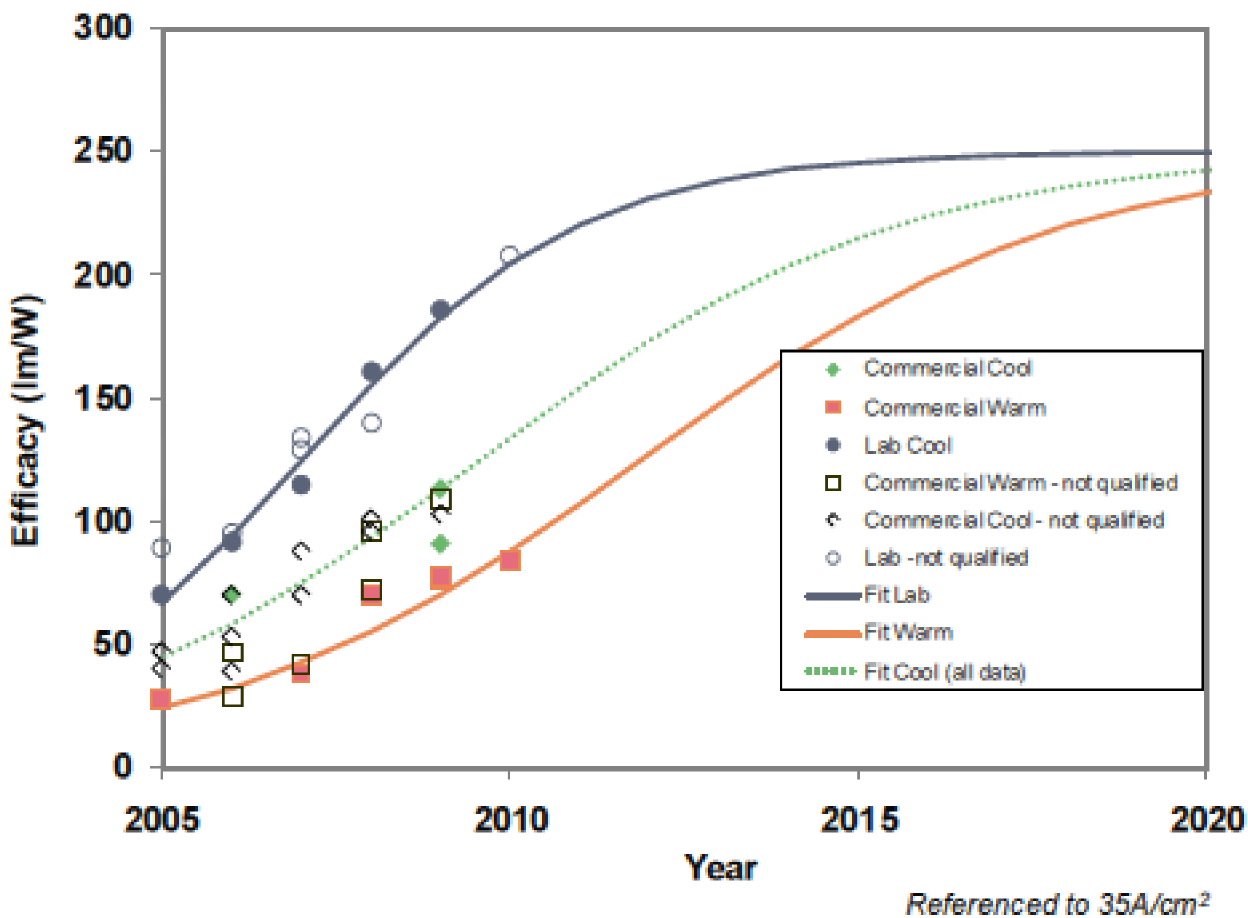
2000s – ...

Why Now?: Basic Advantages of LED

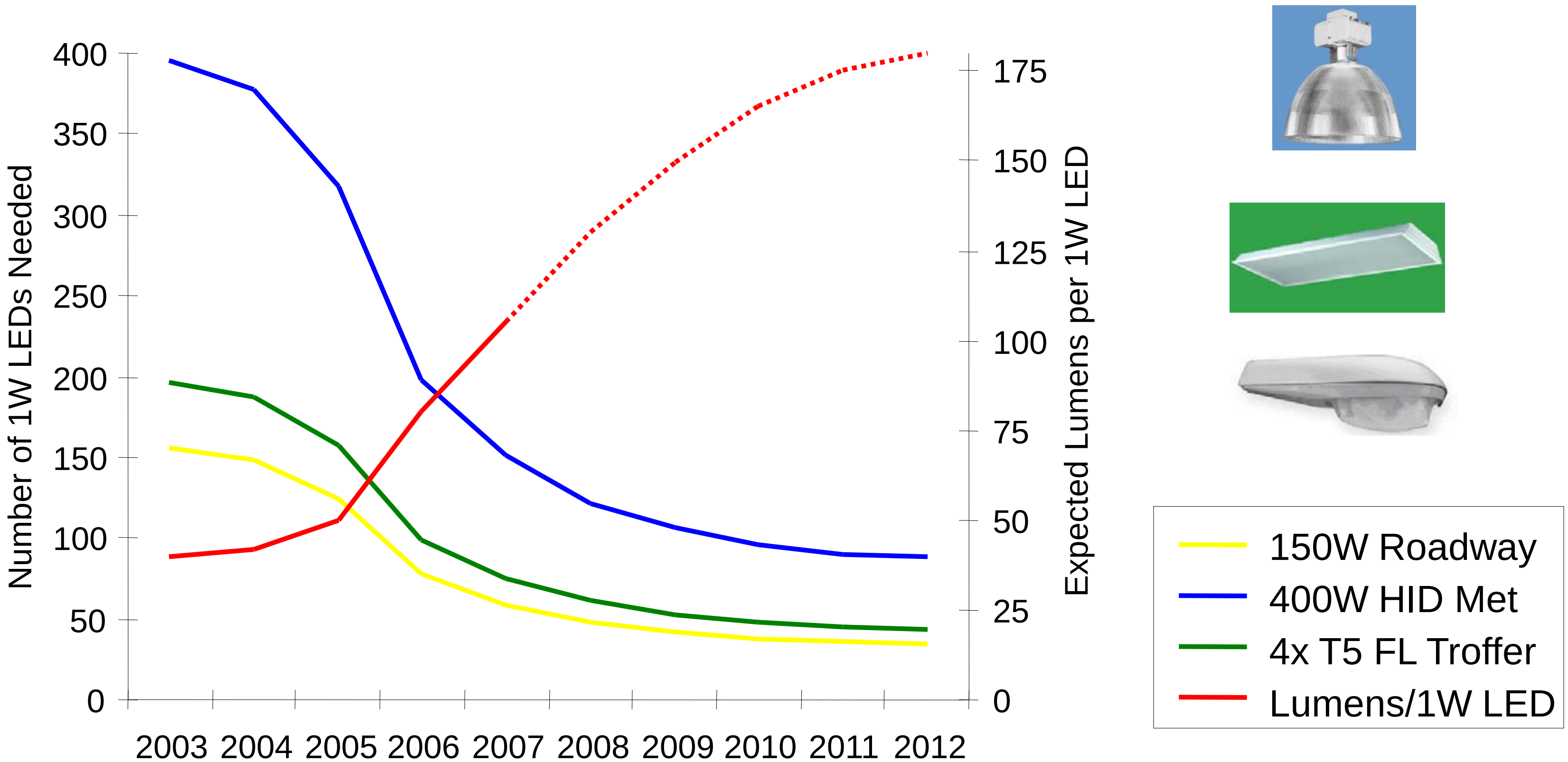
- LEDs are…very **energy efficient** → >150LPW (near-term roadmap to >200LPW…)
- Are **directional** → No wasted light, any pattern possible
- Have very **long lifetime** → >50,000 hours to 70% Lumen Maintenance (L_{70})
- Are inherently **rugged** → No filament to break
- **Start instantly** → nanoseconds vs. > 10 min re-strike (HID)
- Are **environmentally sound** → no Hg, Pb, heavy metals
- Are **dimmable, controllable** → New lighting features, power savings
- Love cold temperatures → **No cold starting issues**



2011 U.S. DOE Roadmap for LEDs



At the Tipping Point On Most C&I Applications...



Led Standards Update

Levels of Standards

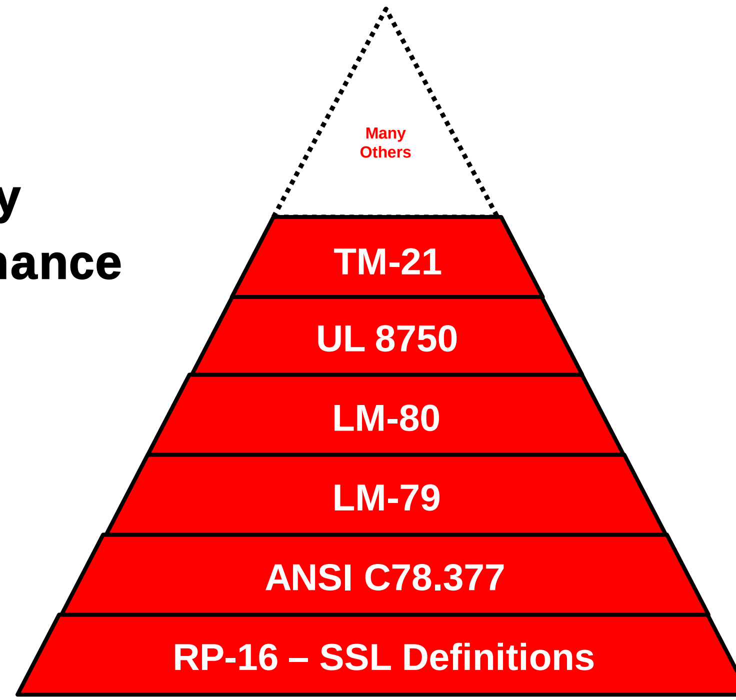
Level	Description	Example
Basic definitions	LED chip, LED lamp, Module, Light Engine…	IES RP-16
LED Component	Color, Lumen Maintenance, Lifetime, Binning…	ANSI C78.377A, IES LM-80, NEMA SSL-3, TM-21
Luminaire	Photometry, safety	IES LM-79, UL 8750
Application	Outdoor, parking	IES RP-8, IES RP-20
Government Program	Energy, utilities	US EPA Energy Star, Design Lights Consortia

LED-specific Standards

LEDs must conform

LED Standards (U.S.)

- 4 years ago: Major and reasonable objection to LED
- Today:
  - RP-16 – SSL Definitions
  - ANSI C78.377 – chromaticity
  - IES LM-79-2008 – SSL photometry
  - IES LM-80-2008 – Lumen Maintenance
  - UL 8750 – Safety
  - TM-21 – Lumen Maint. Projection
- Most of the major pieces are in place, more on the way…
- Being practiced and referenced worldwide by industry and government programs



LED Standards Update

Status of NEMA, ANSI, IES, IEC, and CIE Solid State Lighting Standards (Partial List)

Standard	Draft	Comment	Comment Resolution	Publication Status
IES RP-16 *Definitions*	X	X	X	Complete
ANSI BSR C78.377A, *Chromaticity*	X	X	X	Complete
IES LM 79, *Luminous Flux*	X	X	X	Complete
IES LM 80, *Lumen Depreciation*	X	X	X	Complete
NEMA LSD-44, 45, 49 (White Papers) *Best Practices for SSL Interconnect, Sub-Assemblies, Dimming*	X	X	X	Complete
ANSI C82.77, *Harmonic Emission Limits – Related Power Quality Requirements for SSL*	X	X	X	Complete
NEMA SSL-1, *SSL Drivers*	X	X	X	Complete
NEMA SSL-3, *LED Lamp Binning*	X	X	X	Complete
NEMA SSL-6, *Dimming Practices for SSL Integrated Lamps*	X	X		
NEMA-ALA Joint White Paper *Definition of Functional & Decorative Lighting*	X	X	X	Complete
UL 8750 *LED Safety*	X	X	X	Complete
IEC 62471-2, IES RP-27 *Photobiological Safety*	X	X	X	Complete
IES TM-21 *LED Lifetime*	X	X	X	
47 CFR Part 15 (FCC) *Radio Frequency Emissions for SSL Components, Drivers*	X	X	X	Complete
IEC 62471-2, IES RP-27 *Photobiological Safety*	X	X	X	Complete

LM-79-08 Photometric Testing

How Does it Impact the LED Roadway Luminaire Design and Manufacturing Process???

LM-79-08
IES Approved Method for the Electrical and Photometric Measurements of Solid-State Lighting Products

Requires Absolute Photometry

LM-79-08

- **Absolute Photometry Methods**
  - **Luminaire is Tested as a Complete System**
    - **Accounts for all Contributing Illumination Performance Characteristic System Variables**
      - **Chip Package**
      - **Thermal Management**
      - **Optical**
      - **Electrical**

LM-79-79-08 Data

- Total Luminous Flux
- Luminous Intensity Distribution
- Electrical Power Characteristics
- Luminous Efficacy (calculated)
- Color Characteristics
  - CRI
  - CCT
  - Etc.

Absolute vs. Relative Photometry
Photometric Accuracy
(HID vs. LED)

- **HID Relative Photometry Normalizes Two Significant Variables**
  - **HID Lamp Performance**
    - **A Lamp Calibration Process is Used to Normalize the Lamp Performance (i.e. Luminous Flux) to the Published Value**
  - **HID Ballast Performance**
    - **Testing is Conducted With the Lamp Operating at Rated Power, Regardless of the Required Input Power Characteristics**

Possible HID Lamp Variation

- Initial Luminous Flux at Rated Lamp Power
  - For a Wide Range of Lamp Manufacturers
  - ± ~15%
- Lamp Operating Voltage Rise at End of Life
  - ~10%

HID Magnetic Ballasts

- **Lamp Power Regulation**
  - **Reactor – very poor**
  - **CWA - better**
  - **Mag-Reg / Reg-Lag – even better**

Gonio-Photometric Accuracy

- **Repeatable Results Accuracy…**
  - **± ~2.5% for Total Luminous Flux**
  - **± ~5% For Luminous Intensity at Angle**

CALiPER Qualified Labs Are Held to a Higher Standard of Accuracy

Stacking it All Up…

- **Assume ±5% Power Variation and CWA Ballast**
  - **Combined Results: Lamp Variation Factors / Power Regulation Factors / Photometric Testing Variation Factors / Etc…**

Lamp Variation / CWA Ballast Variation / Total Flux Testing Variation
→ ~±20% Range for Illumination Predictability???

CWA Ballast Variation / Lamp Power Increase
→ ~±10% Range for Power Consumption Predictability???

Other Contributing Variables For HID Systems

- **Lamp Geometry Variability???**
- **Lamp Positioning Variability???**
- **Optical System Variability???**
- **Poor/Accelerated Lumen Maintenance Due to Unexpected Lamp Operating Conditions**
- **Lamp Prorating That Ignores Light Source Geometry Change**

LED Luminaire Variability

- **LED Drivers**
  - Power Regulation to LED Light Engine
    - ± 1% Typical
  - Power Consumption
    - Narrow Range of Variability
- **LED Package (Lamp)**
  - Inventory Management (Binning)
    - Predictability
    - Verification

Application "Fine Tuning" Opportunities

- **A Wide Range of Product Possibilities…**
  - **Small Luminous Flux Increments**
  - **Wide Range of Drive Currents**
  - **Optics**
- **Thousands of Possible Luminaire Configurations…**

Do They All Need to Be Tested???

Photometric Scaling?

Example:

Reference LM-79-08 Photometric Test

- **Type II Medium, 40 LED, at 350 mA**
  - » **Initial Delivered Lumens = 3,420**

- **Type II Medium, 60 LED, at 350 mA**

Multiply Luminous Flux Data by 1.5???

5,130 Lumens

WRONG!!!

Actual Initial Delivered Lumens = 5,041
(1.47 X Reference Test Value (~2% Difference)

Total Luminaire Efficacy
Reference Luminaire (40 LED) – 76 Lumens per Watt
60 LED test – 71 Lumens per Watt = ~7% Difference

Photometric Interpolation

- **Is it Legitimate???**
  - **Derived From LM-79-08 Luminaire Data**
    - **Reference Luminaire**
  - **Accounts For All Contributing Variables**
    - **Thermal Characteristics**
    - **Electrical Characteristics**
  - **Predictable Accuracy**
    - **Within the Range of Photometric Testing Repeatability**

LED Luminaire Performance Validation

- Testing and Documenting in the Manufacturing Environment
  - Total Luminous Flux Data
  - Color Quality Data
  - Electrical Characteristics Data
  - Etc…
- Data Linked to Unique Product Serial Number

LED Lifetime: 50,000 hours is:

137	Years at 1 hour/day
68.5	Years at 2 hours/day
34.2	Years at 4 hours/day
22.8	Years at 6 hours/day
17.1	Years at 8 hours/day
11.4	Years at 12 hours/day
5.7	Years at 24 hours/day

...A WAG when it comes to LED lifetime...

Semiconductor Reliability Testing

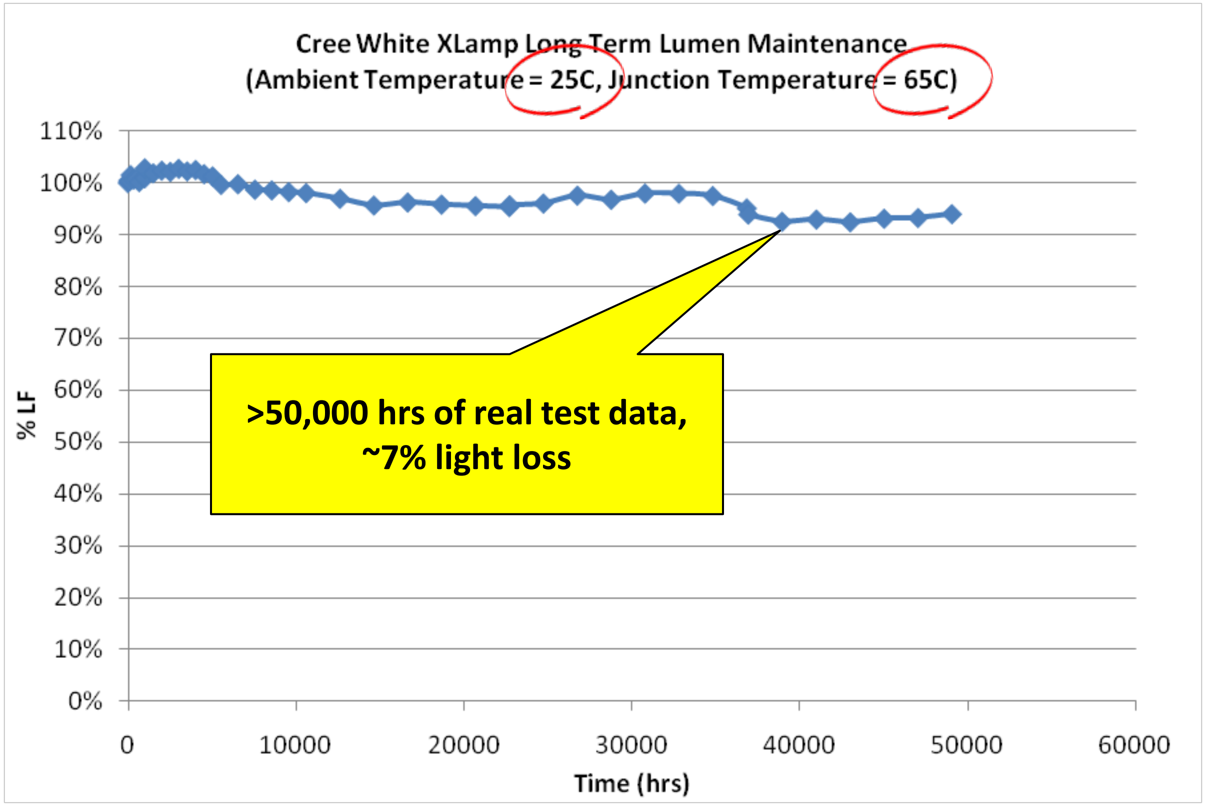
- **Reliability test methods and acceptance criteria for semiconductor components have been standardized (JEDEC, EIAJ, others…) and practiced for decades**
- **Think: processors, regulators, microcontrollers, etc..**

If you've ever flown in an airplane, driven in a car, or talked on a cell phone, you've depended on this body of scientific work and testing…

LED Reliability Testing

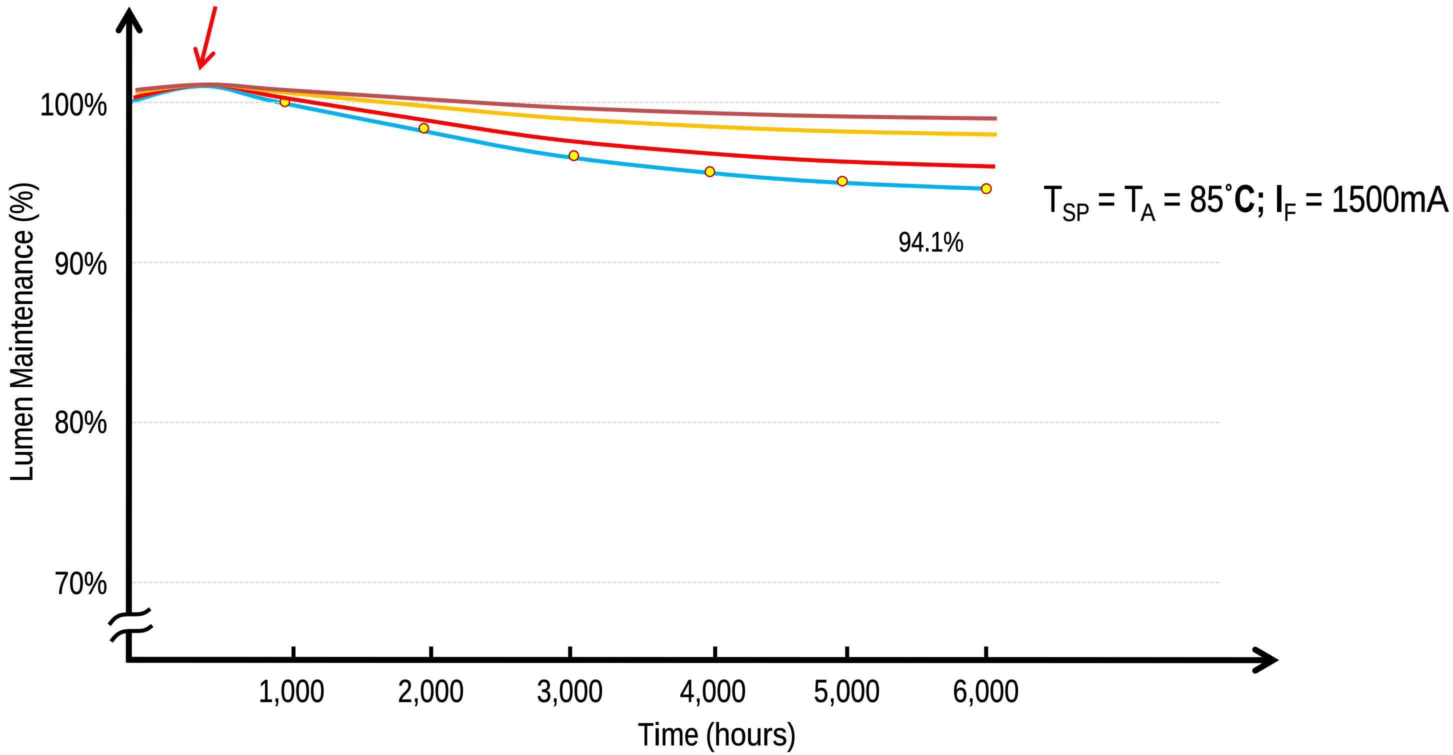
- **LEDs are semiconductor components that happen to emit light…**
- **Most LED manufacturers conduct standardized semiconductor component reliability testing – the same tests Intel tests their microprocessors with – on their LED lamps**
- **The Illumination Engineering Society of North America published IES LM-80 in 2008 to characterize the Lumen Maintenance aspect of LED semiconductor components**
- **Note: Lumen Maintenance ≠ LED Lifetime**

LEDs Last Forever!! [under ideal conditions]



Well-designed systems with Lighting-class LEDs at low T_A, T_J will run a very, very long time…

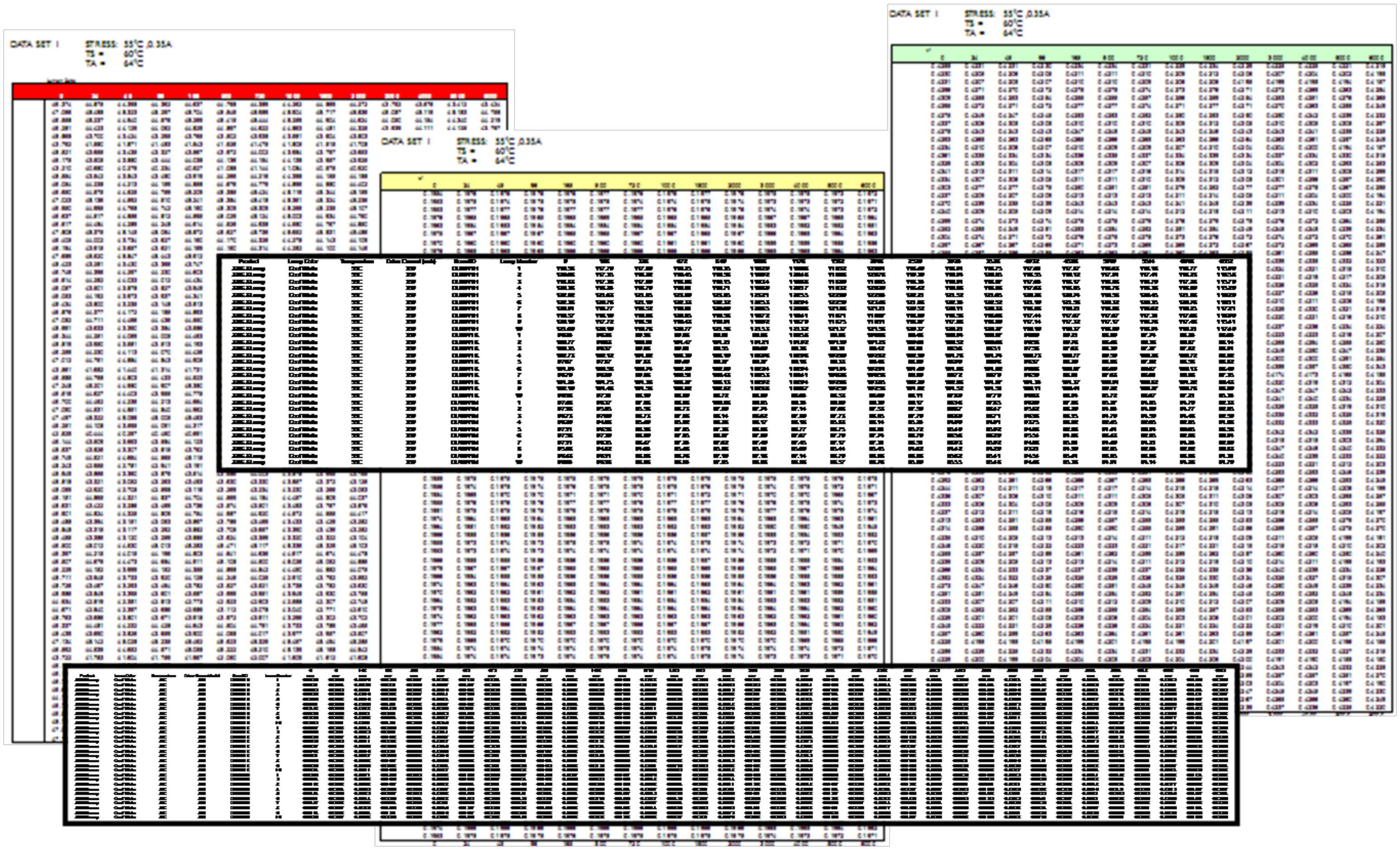
Typical LM-80 Lumen Maintenance Behavior



- LEDs do not normally fail catastrophically; gradually lose light output over very long time periods
- Small "hump" is frequently observed between 0 and 500 hours
- Lower drive currents and lower temperatures yield higher Lumen Maintenance curves

Everyone Asks for an “LM-80 Report”

Here is what one looks like (very detailed, no interpretation, just data…):



LM-80 & TM-21

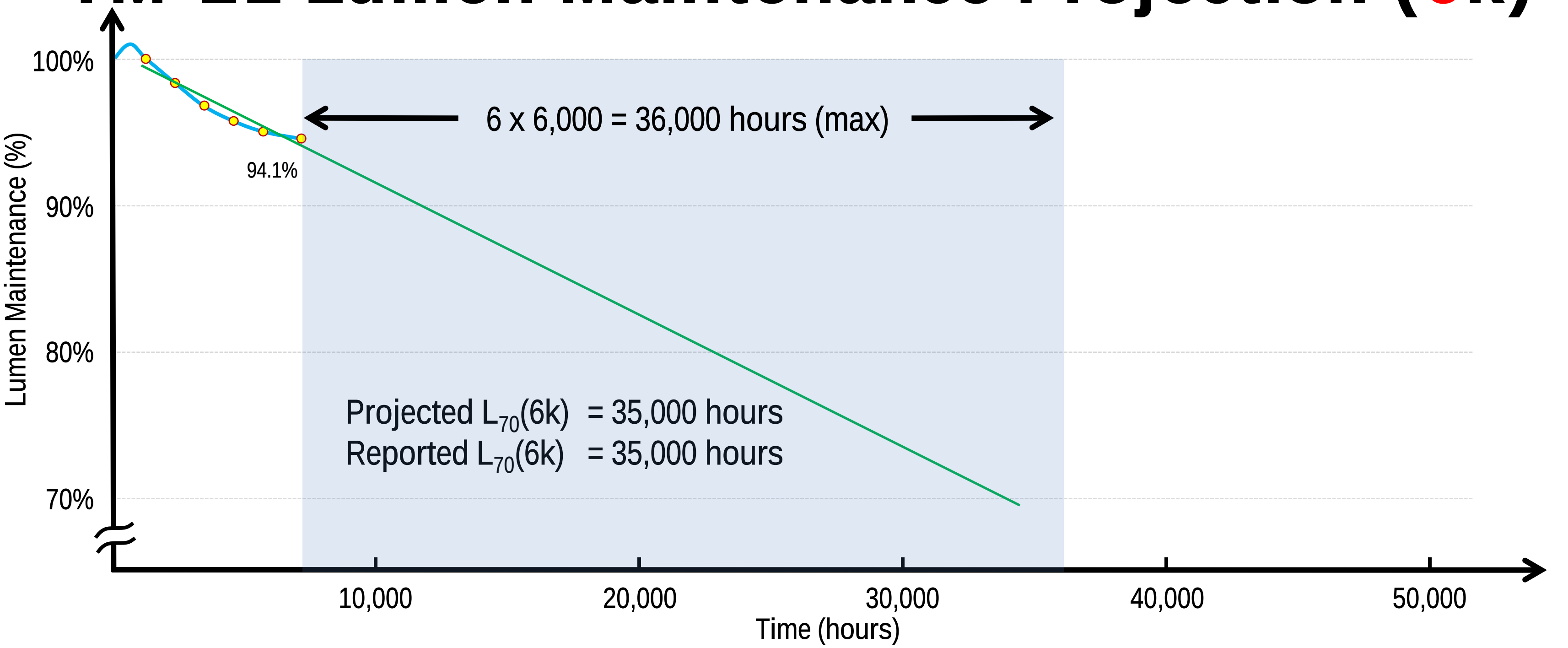
LM-80 (testing) + TM-21 (projection) = Something useful

- **LM-80 is just an LED testing standard**
- **IES TM-21-2011 provides the mathematical framework for taking LM-80 data and making useful LED lifetime projections**
- **Key points of TM-21:**
- **Developed by major LED suppliers with support of NIST, PNNL**
- **Projection limited to 6x the available LM-80 data set**
- **Projection algorithm: least squares fit to the data set**
- **L70, L80, L90, Lxx projections easily possible**
- **Nomenclature: $L_p(Yk)$**

  where p is the Lumen Maintenance percentage and Y is the length of the LM-80 data set in thousands of hours

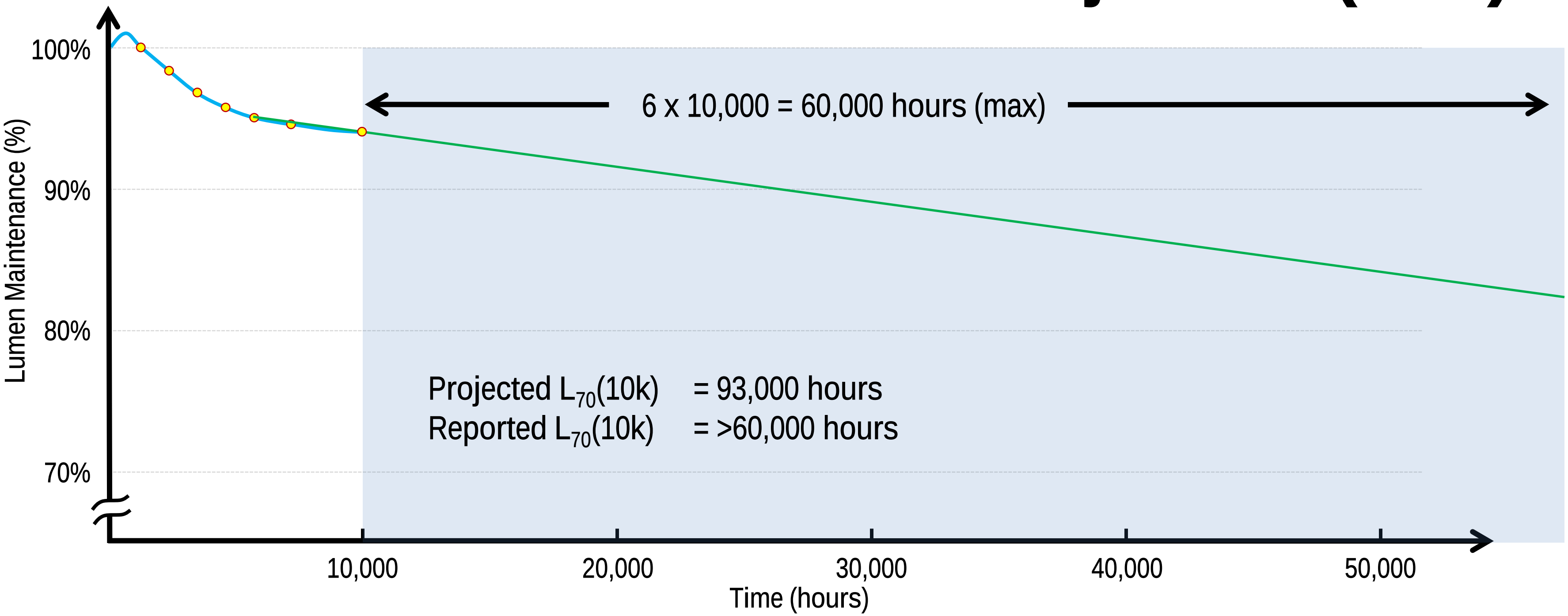
Example: $L_{85}(10k)$

Typical LM-80 Test Behavior and TM-21 Lumen Maintenance Projection (6k)



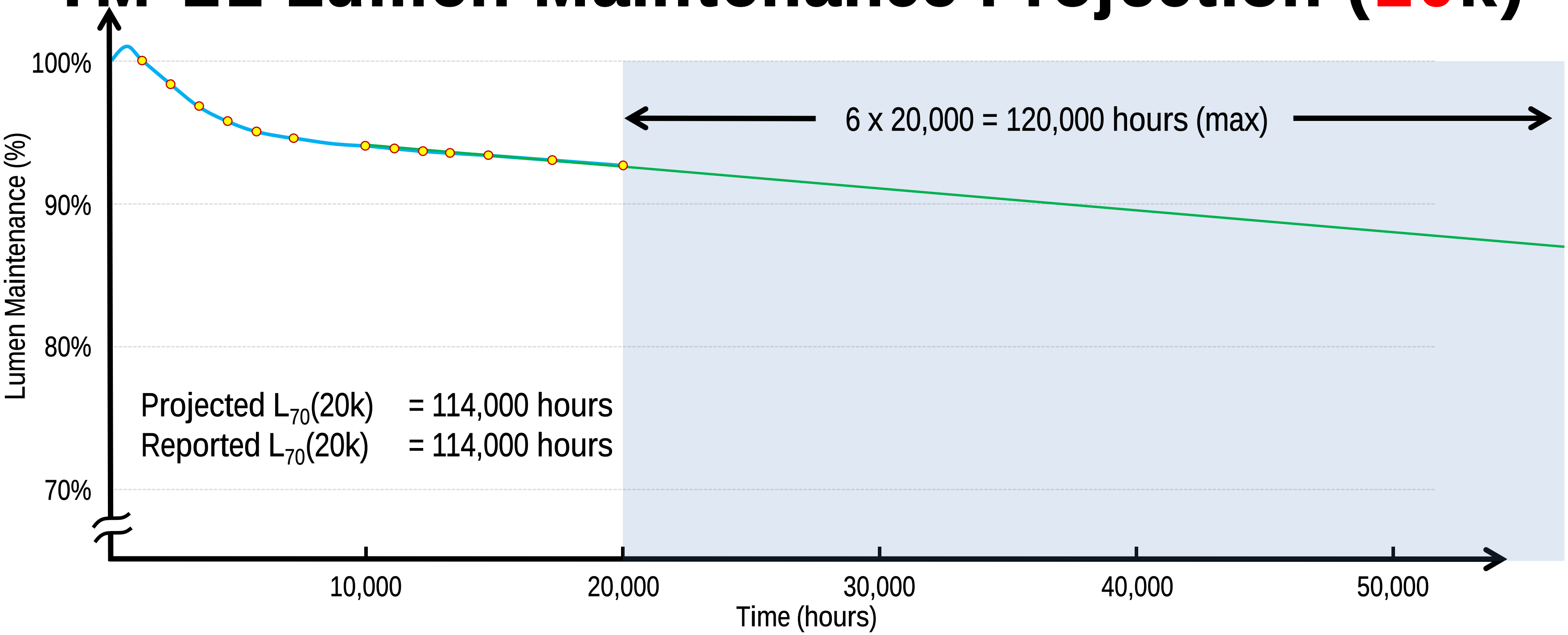
- **First 1k hours is ignored for TM-21 projection purposes**
- **Upper reporting bound set by 6x available data (6 x 6k = 36k hrs)**
- **Exponential extrapolation to least squares mathematical fit between 1k and 6k hours**
- **Reported and projected L70 may or may not be the same number**

Typical LM-80 Test Behavior and TM-21 Lumen Maintenance Projection (10k)



- $T_{max/2}$ is used for TM-21 projection (10K/2 = last 5K hours)
- Upper reporting bound set by 6x data (6 x 10k = 60k hrs)
- Exponential Extrapolation to least squares mathematical fit between 5k and 10k hours
- Reported and projected L_{70} may or may not be the same number

Typical LM-80 Test Behavior and TM-21 Lumen Maintenance Projection (20k)



- $T_{max/2}$ is used for TM-21 projection (20K/2 = last 10K hours)
- Upper reporting bound set by 6x data (6 x 20k = 120k hours)
- Exponential Extrapolation to Least squares mathematical fit between 10k and 20k hours
- Reported and projected L_{70} may or may not be the same number

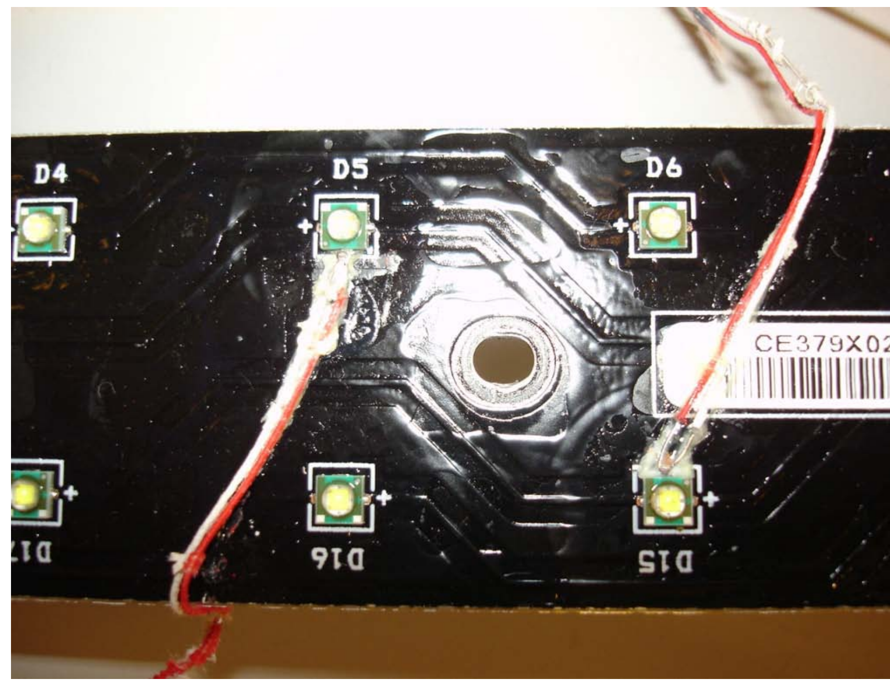
Lumen Maintenance Levels for Lighting Design (Reported, Example*)

	6k	10k	20k
L_{95}	10,000	14,000	15,000
L_{90}	19,000	21,000	25,000
L_{85}	28,000	33,000	39,000
L_{80}	>36,000	44,000	59,000
L_{75}	>36,000	55,000	85,000
L_{70}	>36,000	>60,000	114,000

*** Example only, not real data**

Zone*	Drive Current (mA)	Initial LD	25K hr LD	50K hr LD	100K hr LD
5°C (41°F)	350mA	1.05	1.01	0.97	0.89
	525mA	1.05	0.96	0.90	0.77
	700mA	1.05	0.90	0.81	0.64
10°C (50°F)	350mA	1.04	0.99	0.95	0.86
	525mA	1.04	0.94	0.87	0.74
	700mA	1.04	0.88	0.79	0.60
15°C (59°F)	350mA	1.03	0.96	0.92	0.83
	525mA	1.03	0.91	0.84	0.71
	700mA	1.03	0.85	0.76	0.57
20°C (68°F)	350mA	1.01	0.94	0.89	0.80
	525mA	1.01	0.88	0.81	0.67
	700mA	1.01	0.83	0.73	0.53
25°C (77°F)	350mA	1.00	0.91	0.86	0.76
	525mA	1.00	0.86	0.79	0.64
	700mA	1.00	0.80	0.70	0.50

*Average Nighttime Temperature



LED Lifetime Is Irrelevant

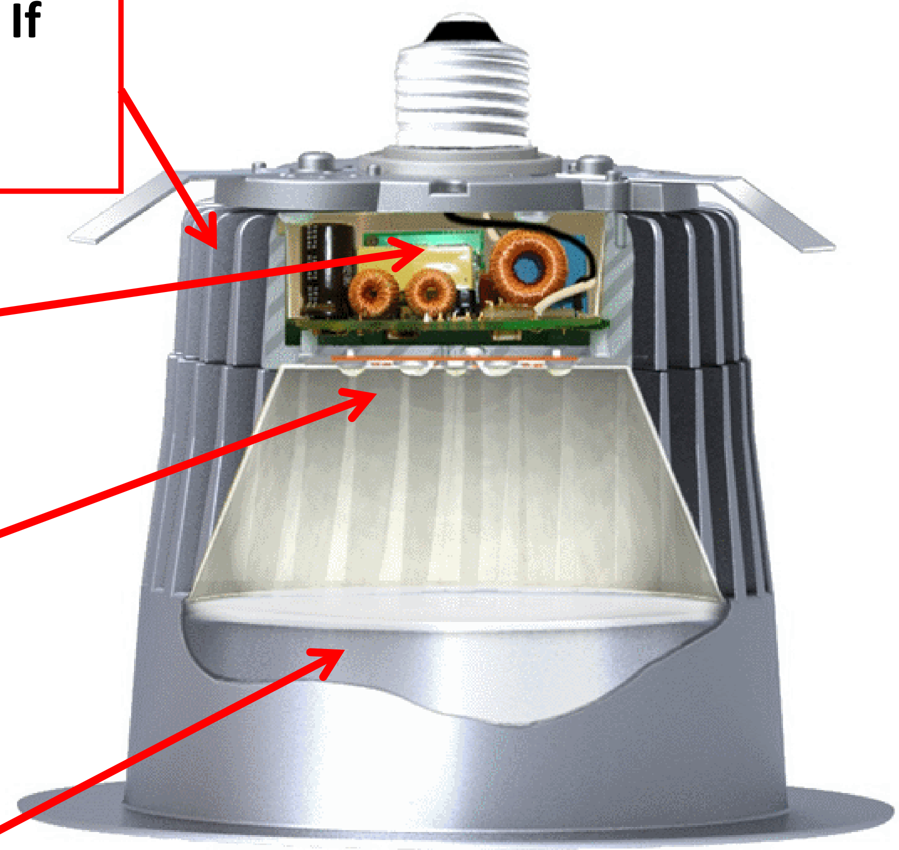
System Lifetime is What Creates Value

Heat Sink: Linchpin of the entire system. If this is poorly designed, all the other components can be compromised

Driver: Currently the weakest point of the system, but the big companies are working on this

LED Lamps: Practically never fail; depreciate very slowly in a well-designed system

Optical Components: Can (rarely) yellow over time and lose light; system design choice



When The End Comes / When Does The End Come?

- **Literally *any* scheme you can imagine is implementable**

- **The market – *you*! – will ultimately decide between**
  - **Maintenance schedules**
  - **Let it run**
  - **Simple shut down**
  - **Blinking (codes, colors)**
  - **Constant lumens, mean LPW**
  - **Playing song…**

Wrap-up

- **LED are different…**
  - **…standards**
  - **…photometry**
  - **…lifetime**
  - **…value creation**
- **There is a lot of hype and over-stated marketing claims around LEDs –**
  - **Education is the best way to overcome this…**
- **LEDs are going to bring in a new level of rigor to the lighting world**
- **LED can save energy, save money, and protect the environment –**
  - **In some applications today, on others, just a few years**